Assessing Hypocentral Accuracy and Lower Magnitude Completeness in the Pacific Northwest Using Seismic Refraction Detonations and Cumulative Frequency-Magnitude Relationships

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Introduction

Absolute hypocentral location errors are traditionally estimated from the errors in the location of quarry blasts. Catalog completeness has been evaluated by examining cumulative frequency-magnitude relationships (e.g., Rydelek and Sacks, 1989). In the Pacific Northwest, however, the number of quarries with well-defined blasting schedules is relatively sparse (e.g., Benson et al., 1992). Seismic refraction detonations provide an independent assessment of actual location errors of surface events in the Pacific Northwest and elsewhere. Because the detonation yields are also known, their reported magnitudes can be used to investigate the detection and location thresholds for low magnitude earthquakes. As the number and distribution of seismic stations in the Pacific Northwest expanded (Figure 1), the location accuracy of the networks and the completeness of their catalogs has improved with time. Because the station coverage is not uniform geographically, these network properties vary with location.

In this note we use 72 refraction detonations listed in the Advanced National Seismic System (ANSS) and Pacific Northwest Seismic Network (PNSN) catalogs for the Pacific Northwest to investigate the hypocentral accuracy and completeness of the earthquake catalog as a function of time and location since 1984. These reported detonations had an average charge size of 939 kg and yielded an average coda magnitude of 1.65. Applying magnitude-versus-charge-size relationships to 64 detonations not listed in the ANSS and PNSN catalogs permits us to extend our analysis back to 1965. Brocher (2003a) noted several reasons why the location errors for surface detonations may not be fully representative of location errors for tectonic earthquakes. Nonetheless, quarry blasts and refraction detonations represent seismic sources whose origin times and locations are precisely known, and they provide an independent measure of the quality of location solutions by the network. Furthermore, the regional variation in the ability of a seismic network to locate surficial detonations, which can be measured, presumably reflects the regional variation in the ability of the network to locate shallow (near surface to a few km depth) earthquakes, which cannot be measured. We sought to determine whether regional variations exist in the capability of the Pacific Northwest Seismic Network (PNSN) to locate earthquakes in Oregon and Washington.

Growth of the Pacific Northwest Seismic Network

The Pacific Northwest Seismic Network (PNSN) has grown steadily since 1969 (Figure 1). Before 1969, the few regional stations (LON, TUM, SEA, COR, SPO, etc.) were operated individually rather than as a network. In 1969 the U.S. Geological Survey (USGS) installed stations in eastern Washington, near Hanford, and recorded the analog data at Menlo Park, California. The Western Washington array began in 1970 with the installation of five stations in Puget Sound by the University of Washington (SPW, GMW, GSM, BLN, and CPW), yielding earthquake locations beginning in July 1970 (Crosson, 1972). Two additional stations were added in the Puget Lowland in 1971. In 1972, the USGS installed stations at Mt. St. Helens (SHW), Mt. Rainier (FMW), and Mt. Baker (MBW), and recorded the analog data at the University of Washington. Between

1977 and 1979, the USGS installed a network of sixteen analog stations at Mt. Hood, again recorded at Menlo Park, California.

In 1979, 12 new stations on the Olympic Peninsula and 6 stations in the southern Washington Cascade Range were installed and operated by the University of Washington and the U.S. Geological Survey. The first integrated recording of the Western Washington and Hanford networks began in 1979. During 1979 and 1980 the Mt. Hood network was reconfigured by the USGS at Menlo Park to an Oregon Cascade network.

Digital recording started in March 1980 for the Western Washington and Hanford networks. Expansion of the network at Mount St. Helens also began on March 21, 1980. During the summer of 1980 the operation and recording of the Mt. Hood stations were transferred from the USGS to the University of Washington, and additional Olympic Peninsula stations were installed. Between 1980 and 1982, additional stations were installed in northern Oregon, and some stations in the Oregon Cascade network were transferred to the University of Washington. The remaining stations in this Oregon Cascade net were transferred to the University of Washington between 1982 and 1984.

Broad-band stations were added to the network beginning in 1994 and strong motion stations began to be added three years later. Starting in 1998, USGS/NOAA CREST (Consolidated Reporting of Earthquake and Tsunami) stations, designed to detect potentially tsunamigenic earthquakes, were installed and incorporated into the network. In 2000, Seattle was picked as an Advanced National Seismic System (ANSS) pilot site, and 20 new digital, real-time, strong motion accelographs were installed in the Seattle area.

None of the detonations studied here automatically triggered the PNSN network, and thus they do not represent a truly “blind” test of the network. Prior to March 1980, the recording was entirely analog and events were visually scanned from film. Until the PNSN began digital recording in March 1980 there was no possibility of automatically “triggering” data recording by detonations. Through 1999, however, the expected shot times of refraction detonations were preset to allow manual triggering to assure recording of the blasts. Thus, from 1980 to 1999 there was no true automated triggering of the network by these refraction detonations.

Refraction Detonation Database

Between 1978 and 2000, the USGS and its collaborators conducted eight seismic refraction experiments using large chemical explosions detonated electrically in shallow (<60 m) boreholes (Figure 2A). The location and origin times of the detonations are known to within a few tens of meters and to within a few milliseconds, respectively (e.g. Brocher et al., 2000). These higher accuracies provide more stringent tests of absolute hypocentral accuracy than do the ripple-fired quarry blasts often used for calibration of an earthquake catalog.

Brocher (2003b) recently described the drilling, loading, and detonation of these USGS refraction boreholes. The depth of the 20-cm in diameter USGS boreholes are typically designed using an average tamp thickness of 15.3 m and a linear charge density of 42 kg/m. Tamp is typically either well cuttings or sand and gravel loaded on top of the main charge to contain the explosion. The average borehole depth, 38.7 m, for the shots compiled here is thus expected for an average charge size of 939 kg. The detonations studied here range in charge size between 57 and 2715 kg.

Table 1 summarizes many aspects of the located detonations, including detonation location and elevation, detonation date and time, charge size (yield), number of boreholes fired simultaneously, whether the hole was wet or dry, and whether the hole was loaded by hand or by pump truck. Elevations for about half of these detonations have never been previously published. Table 1 also summarizes the earthquake magnitude and hypocentral location reported for the detonations in the ANSS and PNSN catalogs, as well as the quality factor for the PNSN location of the detonation. Locations and relative magnitudes of these detonations are plotted in Figure 2A. Detonation locations and elevations, origin times, charge sizes (yields), and number of boreholes fired simultaneously for detonations not located by the networks are given in Table 2 and their locations are plotted on Figure 2A. Much of this information was derived from unpublished drilling, loading, and shooting logs.

To estimate the magnitudes of detonations not located by the PNSN, we first test an empirical relationship between charge size (yield) and local coda magnitude for the 72 detonations reported in the catalog (Figure 3). Coda magnitudes, M_c, were calculated using $M_c = -2.46 + 2.82 \log$ (average coda length) as described by Crosson (1972). The average coda magnitude for the detonations compiled here, 1.65, indicates that the average coda length is 27.4 seconds (Table 3). The data show considerable scatter in catalog magnitude for a given charge size, reflecting variations in charge coupling and completeness of the detonation. For any given charge size, the largest coda magnitudes for these detonations lie close to an empirical upper limit magnitude (referred to here simply as a maximum magnitude) derived for chemical and nuclear detonations in hard rock (Khalturin et al., 1997),

$$M_{\text{hard rock}} = 0.26 + 0.73 \log_{10} (\text{charge weight, kg}). \qquad (1)$$

In Figure 3 we also plot an empirical relationship between magnitude and charge size for detonations in large bodies of water (Gitterman and Shapira, 2001),

$$M_{\text{water}} = 0.285 + \log_{10} (\text{charge weight, kg}), \qquad (2)$$

which, with its higher slope than equation 1, reflects the improved coupling of such detonations to the surrounding material.

Linear regression of the 72 located detonations in Figure 3, assuming an intercept equivalent to equation (1), yields:

$$M_{\text{linear regression}} = 0.26 + 0.48 \log_{10} (\text{charge weight, kg}) \quad (3),$$

whose slope, 0.48, is only slightly lower than that reported for 311 refraction detonations in California and Nevada, 0.53 (Brocher, 2003b). This result is not surprising given that the techniques used to drill, load, and detonate the boreholes in the Pacific Northwest were identical to those used in California and Nevada.

Expected maximum magnitudes of the detonations that could not be located, calculated from Equation 1 based on their charge sizes, are also provided in Table 2. In addition to these land-based studies, three onshore-offshore seismic refraction experiments were conducted in the 1990s using large marine airgun arrays (Figure 2A).

Detonations Listed in the ANSS and PNSN Catalogs

The first refraction experiment for which detonations are listed in the ANSS and PNSN catalogs was conducted in 1984 in the Columbia Plateau, within the Hanford network (Cotton and Catchings, 1988). All seven detonations used for the experiment (Cotton and Catchings, 1988; Col. Plat. in Table 1) were located by the PNSN (Figure 2A). Several additional temporary stations were deployed to record these detonations.

Two long, N-trending, seismic lines and a shorter E-trending line were shot in western Washington and Oregon in 1991 using a total of 26 detonations (Figure 2A). One line was located in the eastern side of the Puget Lowland in Washington and the other was collected in the eastern Coast Range of Washington and Oregon (Luetgert et al., 1993). The shorter E-trending line was located along coastal Oregon (Tréhu et al., 1993). All but four of the detonations were located by the PNSN. The estimated magnitudes of the reported detonations were between 0.0 and 2.6 (PNW91 in Table 1). One additional detonation, SP 1, located at the northern edge of the PNSN array near the Canadian border (Figure 2A), was detected but could not be located by the PNSN (Table 2).

An E-W seismic refraction line in 1995 stretching from the coast across the Cascade Range to the Columbia Plateau at the latitude of Grays Harbor, Washington used 31 detonations (Parsons et al., 1998). Twenty-six of these detonations, with magnitudes between 0.2 and 2.2, were located by the PNSN (Figure 2A, PNW95 in Table 1). Five additional detonations, mainly east of the Cascades, were detected but not located by the PNSN (Figure 2A, Table 2).

Finally, in 1999 the SHIPS99 Working Group detonated 34 shotholes along another E-W striking seismic refraction line at the latitude of Seattle, Washington (Brocher et al., 2000a, b). Sixteen of these detonations were located by the PNSN with magnitudes between 1.0 and 2.7 (Figure 2A, SHIPS99 in Table 1). Another 13 detonations were detected but could not be located by the PNSN (Figure 2A, Table 2). Five detonations went undetected.

Detonations and Airgun Shots not listed in the ANSS and PNSN Catalogs

A refraction study in the vicinity of Mount Hood, Oregon in 1978 used 15 detonations (Figure 2A) (Kohler et al., 1982; Leaver et al., 1984). These 452- to 2700-kg charges (Mt. Hood in Table 2) produced useful signals to offsets as much as 80 km (Kohler et al., 1982) and were recorded by the Mt. Hood network (Figure 1). Not surprisingly in view of the few stations operating at this time, none of the shots were locatable and none of these shots are listed in the ANSS and PNSN catalogs.

This Oregon study was followed by two others in 1983 and 1984 (Figure 2A). Detonations used for the 1983 Oregon (Oregon in Table 2) and the 1984 Newberry (Newberry in Table 2) experiments may have yielded magnitudes up to 2.2 and 2.8, respectively. None of these detonations are listed in the ANSS or PNSN catalogs, despite yielding useful arrivals to distances of more than 100 km on temporary recorders (Kollmann and Zollweg, 1984; Leaver et al., 1984; Dawson and Stauber, 1986; Cotton and Catchings, 1989). From 1978 to 1984, the few stations operating in Oregon detected but could not locate these detonations.

Between 1994 and 1998 large airgun sources were used for three different marine profiles near Cape Blanco, Oregon (not shown), offshore central Oregon and Washington ("Sonne" in Figure 2A), and in the Puget Lowland (SHIPS98 in Figure 2A) (Brocher et al., 1995, 1999, 2001; Flueh et al., 1997). These studies used airgun array volumes and pressures comparable to those used during a 1991 BASIX study in the San Francisco Bay area (Brocher et al., 1994) that were located by the Northern California Seismic Network (NCSN) with an average magnitude of 0.4. Symons (1998) estimated a coda magnitude of approximately 0.0 for the SHIPS98 airgun shots. In the Pacific Northwest, none of the airgun shots were located, due to their small magnitude and the sparsity of the coastal network (Figure 1).

Finally, in 2000, four small (68-kg) detonations in Seattle (Brocher et al., 2000) were not located (Figure 2A). SP2 and SP3 were detected by the PNSN but could not be located (SHIPS00 in Table 2). SP1, which was a poor shot, and SP4, which produced strong records on refraction recorders, were not detected.

Epicentral Accuracy

For the 72 detonations listed in the ANSS and PNSN catalogs (Table 1), we computed the actual error in absolute epicentral locations, the actual error in the absolute latitudinal component of the epicentral location, and the actual error in the absolute longitudinal component of the epicentral location (Figures 2B-2D). To calculate actual errors in latitudes, the absolute value of the difference between known and catalog latitude (in degrees) for each event was multiplied by 111.195 km. Actual longitudinal errors were calculated as the absolute difference between known and catalog latitudes (in degrees) for each event multiplied by 111.195 km * cosine (latitude). Comparison of these results to those generated using more precise formulas indicate that these relations are accurate to 100 m or less. Total horizontal errors were calculated from the square root of the sum of the squares of the errors in latitude and longitude.

On average, the total actual epicentral error for the 72 detonations is 1.86 km; however, the resolution of the network is anisotropic (Table 3). The average latitudinal component of the epicentral error, 1.05 km, is smaller than the average longitudinal component of the epicentral error, 1.33 km. Detonations in Oregon are systematically located too far to the north (Fig. 2C). Detonations in the Seattle basin are systematically located too far to the west, and detonations along the Oregon and Washington coasts and near the Canadian border are systematically located too far to the east (Fig. 2D).

Average epicentral location errors are lowest for the 1984 detonations in the Columbia Plateau (0.64 km) and are largest for the 1991 detonations in Washington and Oregon (2.36 km). Average epicentral location errors for the 1995 and 1999 detonations (1.72 km and 1.91 km, respectively) in western Washington are intermediate between those in 1984 and 1991. Thus, the average epicentral location errors do not monotonically decrease with time, but rather, reflect the geographic station coverage at the time.

Table 3 provides a breakdown of these averages for different regions in Washington and Oregon; where "Oregon" is here defined to lie south of 46˚N (as in Figure 5). The division between eastern and western Washington was assigned as 121˚W (as in Figure 5). The Puget Lowland is a subset of western Washington, shots within the Puget Lowland come mainly from SHIPS99 and a few from PNW91. Regardless of how Washington is subdivided, location errors and parameters for the various regions are generally comparable and distinct from those for Oregon (Table 3). In Oregon, fewer stations were used to locate the detonations (which were all fired during the PNW91 experiment), the maximum azimuthal gaps are larger, and the nearest station is more remote from the shot than in Washington (Table 3). As a consequence, location errors in Oregon are nearly double those in Washington. Actual longitudinal errors of several of the SHIPS99 shots in central Puget Lowland are surprisingly large (Figure 2D), resulting in somewhat higher average errors than for Washington as a whole (Table 3).

Two quality factors indicate the reliability of hypocentral locations in the PNSN catalog. The first quality factor is based on travel time residuals (RMS). For the first quality factor, an A quality requires an RMS less than 0.15 sec while D quality has an RMS of 0.5 sec or more (estimates of the uncertainty in hypocenter location also affect this quality parameter). The second quality factor is estimated from the station distribution around the location. These include the largest azimuthal gap in the stations, the number of stations used in the location, and the distance to the closest station. The location quality is generally higher with smaller azimuthal gaps and larger numbers of stations. For this second factor, quality A requires a solution using 8 or more phases, a maximum azimuthal gap less than or equal to 90˚, and a distance to the closest station less than or equal 5 km or to the depth, whichever is greater. A quality D solution has 5 or fewer phases, an azimuthal gap greater than 180˚, and distance to the closest station greater than 50 km.

In Figure 2F we plot in map view the RMS error for the located detonations. There are very few regional differences in the RMS error (Table 3). There is, however, a clear correlation between the number of stations used to locate the detonation, the distance to the closest station, and the largest azimuthal gap (Figures 2G, 2H, and 2I). These maps also correlate with plots of the epicentral errors for these detonations in Figure 4A to Figure 4C for increasing quality factors. As the quality of the hypocentral locations of the detonations is increased from low quality solutions rated DD to higher quality solutions rated BB or higher (Figure 4A to 4C), average epicentral errors decrease from 1.86 km to 1.06 km, and average depth errors decrease from 3.46 km to 1.76 km. Most of this improvement is accomplished simply by eliminating the D quality events from the average (e.g., retaining only events having an RMS error less than 0.5 sec, having more than 5 phases, an azimuthal gap less than 180˚, and a closest station distance less than 50 km).

It is noteworthy that apart from one exception, all of the BB or higher quality locations for the detonations lie within Washington (Figure 4C). This result reflects, in part, the relative sparsity of stations in Oregon (Figure 1), that result in a large azimuthal gap between stations and a low number of stations used in the locations (Figures 2G, 2H, and 2I). It also reflects in part the availability of detailed station corrections, particularly in Western Washington, compared to other parts of the network that have lower rates of seismicity. A similar result was noted when we plotted the locations of the entire ANSS and PNSN earthquake catalogs in Washington and Oregon for 1970 and 2000 as a function of quality of the location (in Figures 4D to 4G).

Hypocentral Depth Accuracy

It is widely known that the hypocentral depths of shallow events are difficult to determine accurately. Depth errors are generally larger than epicentral errors and are best constrained when the nearest station is located within one focal depth of the event. We compiled the actual error in absolute hypocentral depth for the 72 detonations located by the networks in Table 1 (Figure 2E). To calculate these errors we assumed a surface location for the detonation and used the PNSN reported depth as the depth error. The average actual depth error is 3.46 km for these shallow detonations (Table 3).

Errors in the calculated origin times are provided in Table 1. Positive values in this table indicate that the calculated origin time occurred after the actual origin time: the average and median origin time errors indicate a delay of 0.76 and 0.64 seconds from the actual origin times, respectively. Calculated origin times occur before the actual origin time only for about 10% of the shots. Origin time errors are systematically large, and positive, for shots located in the Seattle basin (SHIPS99) and the Willamette Valley

(PNW91), suggestive that the velocity models used to locate these events do not fully account for the travel time delays produced by these basins.

Table 3 summarizes the depth errors for Oregon and various regions in Washington. The smallest depth errors are located in central Puget Lowland (Table 3; Figure 2E), where many of the depth errors are so small that their symbols are not visible in Figure 2E. The largest absolute depth errors are generally found in central Oregon (Table 3). Presumably due to the increased spacing between stations in Oregon, average depth errors in Oregon are 3 to 5 times higher than in Washington.

Yield Variability

Most of the detonations produced apparent coda magnitudes considerably lower than the upper limit curve for solid rocks (equation 1), some as much as 1.5 magnitude units lower (Figure 3). We examined the variability in recorded magnitude produced by 12 shotpoints that were used more than once with charges of the same size. For these repeated detonations the recording station geometry and detonation geometry are identical. The average difference in recorded magnitudes between the first and second detonation was 0.3, considerably less than the scatter shown in Figure 3. We thus believe that most of the scatter shown in Figure 3 and Table 1 reflects variations in charge coupling and completeness of the detonation. Differences in explosive type do not explain the scatter; starting in 1991 the explosive formulation has been the same (either pumped IREGel or Dynoflo). Prior to 1991 boxed DuPont TOVEX Extra HP formula was used.

There are seven detonations (about 10% of the total located), however, whose yield matched or exceeded the maximum magnitude given by equation 1 (Table 4). To better understand what made these shots so efficient, we have compared the details of their drilling, loading, and detonation to the seven least efficient shots in our compilation

(Table 4). This information was derived primarily from unpublished drilling, loading, and shooting logs.

SHIPS99 Shotpoint 20 was the most efficient detonation in our compilation (Table 4), reaching nearly the magnitude expected for charges detonated in large bodies of water (equation 2 in Figure 3). The unexpected efficiency of this detonation, located near the University of Washington campus in Seattle, roused many nearby residents at 2:44 AM local time (Brocher et al., 2000b). The detonation of SHIPS99 Shotpoints 18 and 20, both having reported magnitudes of 1.9, were widely felt in a 1 to 2 mile radius of each shotpoint, and resulted in several inquiries and complaints to the 911 operator, local media organizations, and to the offices of the Seismology Laboratory at the University of Washington, Seattle. These complaints resulted in a formal public apology by the USGS for failing to provide adequate prior notification of the shots.

Brocher (2003b) recently reviewed many of the potential causes for incomplete detonation and poor shot coupling. Brocher (2003b) concluded from an analysis of loading logs that location of the detonation within the watertable was neither a necessary nor sufficient condition to produce an efficient shot for detonations in California and Nevada. In the Pacific Northwest, however, 69% of the located detonations were detonated in wet boreholes (Table 1) and 86% of the most efficient shots were detonated in wet boreholes whereas 57% of the least efficient detonations were detonated in dry boreholes (Table 4). We conclude that in the Pacific Northwest, locating the detonation in the water table may be more important than in California and Nevada.

Brocher (2003b) concluded that hand loading of well tamped boreholes provided the most efficient detonations. Tamp is used to contain the explosion and to prevent gases from venting to the surface. Table 4, comparing the least and most efficient detonations in our compilation, appears to support this conclusion in the Pacific Northwest. Measures of the effectiveness of the tamping including observations of cratering, geysering, and casing blow out. None of the seven most efficient shots produced craters or blew out casing: half of the seven least efficient shots did both (Table 4). Only 20% of the seven most efficient shots produced geysering; 83% of the seven least efficient shots did so (Table 4). The most efficient shots used more tamp: the average depth to the top of tamp was 9.3 m less for the seven most efficient shots than for the seven least efficient shots.

For detonations in California and Nevada, Brocher (2003b) found that hand loaded shots were generally more efficient than pump loaded shots. This find is only weakly borne out by our compilation. Two out of 7 of the most efficient detonations in Table 4 were hand loaded, whereas all seven of the least efficient detonations in Table 4 were loaded by pump truck.

Brocher (2003b) reported that nearly half of the most efficient detonations in California and Nevada were located in either alluvium or playa deposits whereas almost all of the least efficient detonations were located in hard rock. This result is consistent with our compilation of the most efficient detonations in the Pacific Northwest. All but one of the seven most efficient shots in the Pacific Northwest were also detonated in either soft rocks or glacial deposits (Table 4). Only one of the most efficient detonations in the Pacific Northwest was fired in hard rock (basalt). The geology is known for only two of the least efficient detonations in the Pacific Northwest, both were also fired in soft rock (Table 4).

Finally, the fact that coda magnitudes are largely a function of the duration of shear waves in the coda begs the question of how these detonations excite shear wave energy. One possibility is that locally rough topography at the shothole generates scattered shear wave energy, increasing the coda duration and coda magnitude. In support of this hypothesis, we note that two of our most efficient shots, SP 18 and 20 from the SHIPS99 experiment, were located near large bluffs. However, this hypothesis remains a research topic as we have not yet systematically examined or quantified the surface roughness at our shotpoints.

Catalog Completeness at Low Magnitudes

To estimate the threshold of completeness of the earthquake catalog as a function of time and location we plotted a series of cumulative frequency-magnitude curves for Washington and Oregon (Figure 5). We plotted curves for five different subsets of the catalog: (1) Washington state, (2) Oregon, (3) northwestern Washington, (4) eastern Washington and Oregon, and (5) southwestern Washington and northwestern Oregon. These divisions correspond to many of those used in Table 3. Although the network has a denser station spacing in some locations, such as the Puget Lowland, Hanford, and Mt. St. Helens regions, and will have lower magnitudes of completeness in these areas (e.g. Grant et al., 1984), we are more interested in a regional view of the completeness threshold. The geographic subregions for which earthquakes were selected from the ANSS and PNSN catalogs are indicated on Figure 5.

We used these plots to estimate the lower magnitude completeness of the catalog between 1970 and 2000 in these different regions. Arrows on Figure 5 provide estimates of the completeness magnitude for 1970-1980 (black arrow) versus the current completeness magnitude (gray arrow). The dotted lines approximate the slopes of the curves where the magnitudes are completely reported. The arrows are positioned at the lowest magnitudes that lie less than 2% below the dotted lines. We included all events, including both in-slab and crustal earthquakes. We summarize these estimates in Figure 6, in which we show the lowest magnitude of catalog completeness versus year for Oregon and Washington.

Superimposed on Figure 6, we have plotted the recorded magnitudes of detonations that are listed in the ANSS and PNSN catalogs from 1984 to 1999. The lowest magnitudes of these detonations generally decrease over time, in close agreement with the decreasing completeness magnitude of the PNSN. In all cases, however, some detonations yielding magnitudes smaller than the nominal magnitude threshold of catalog completeness were located. The magnitude threshold of catalog completeness in Oregon, for example, has decreased from M=3 from 1970 to 1980 to M=1.8 from 1980 to 1990, to M=1.5 starting in 1990 (Figure 5B). The magnitude threshold of catalog completeness in Washington has declined less dramatically from 1970 to the present, but has decreased from M=1.9 from 1970 to 1985, to M=1.5 from 1985-1990, and to M=1.4 starting in 1990 (Figure 5A).

The maximum expected magnitudes of the detonations and airgun shots not located by the PNSN since 1978 are also plotted on Figure 6. The failure to locate the 1978 detonations in east-central Oregon (Figure 6, Table 2) is consistent with the estimated M=3 level of catalog completeness in Oregon at this time (Figure 5B). The projected maximum magnitudes of the 1983 detonations in eastern Oregon that were not located (Table 2) lie just above the estimated threshold of detection for eastern Oregon of M=1.8 for this date (Figure 5D). Similarly, the projected magnitude of the 1984 detonations in east-central Oregon which were not located by the network (Table 2) lies above our estimated threshold of catalog completeness for Oregon of M=1.8.

The failure to locate the marine airgun array shots in the 1990s can be readily understood as their expected magnitudes lie well below the completeness magnitude threshold for this interval (Figures 5 and 6). Apart from SHIPS98 shots most of these shots were situated at or beyond the boundaries of the PNSN, making them difficult to locate.

For the most part, detonations in the 1990s that were not located were most likely either incompletely detonated and/or poorly coupled. We prefer this explanation for the inability of the network to locate these detonations since these detonations generally were in proximity to other detonations that were located by the PNSN (Figure 2A).

Discussion

The magnitude of the detonations located by the PNSN are consistent with empirical charge size-magnitude relations (equation 1 and 2), which for the most part, were developed for larger charge sizes than used here (Khalturin et al., 1998; Gitterman and Shapira, 2001). Our results for detonations as small as 57 kg and a similar compilation for California and Nevada (Brocher, 2003b) appear to validate the accuracy of these relationships for charge sizes as small as 25 kg. For both studies Equation 1 is exceeded by only 10% of the USGS detonations, which are designed to radiate seismic energy. Equations 1 and 2 provide a method for forecasting the maximum magnitude expected for a given charge size, or the maximum charge size for a given magnitude. These important relations have a variety of forensic uses (e.g., Holzer et al., 1996; Koper et al., 2001), and are used in Comprehensive Nuclear Test Bay Treaty monitoring (e.g., National Academy of Sciences, 2002).

For the most part the maps shown in Figure 2 can be readily understood in terms of the station densities shown in Figure 1. Low station density in Oregon, for instance, is associated with low numbers of reporting stations, large closest-station distances, and large azimuthal gaps (Table 3). There are some surprises, however. The large errors in absolute longitude reported for several of the detonations from SHIPS99 in Puget Lowland (Table 3) were unexpected given the relatively large number of stations in that area (Figure 1). The most plausible explanation for these large location errors is that the simple 1-D velocity model, station corrections, and station weighting scheme do not adequately reflect the structural complexity of the Puget Lowland (e.g. Brocher et al., 2001). There is a lack of correlation between epicentral and depth errors and the RMS error (Table 3), indicating that for this small range of RMS error, the RMS error is not a reliable measure of these uncertainties.

Comparison of the completeness magnitude based on cumulative frequency-magnitude analysis with the magnitude of detonations (Figure 6) gives insight into the completeness of the ANSS and PNSN catalog at low magnitudes at a regional scale. Although a general decrease in completeness magnitude would be expected as station density increases, Figures 5 and 6 quantify these estimates. For western Washington and northwestern Oregon the completeness magnitude since the mid 1980s lies between 1.4 and 1.5 (Figures 5C and 5E), although smaller events are detected. Given the fact that the recording of the detonations was manually triggered, this formal estimate may be slightly too optimistic. We propose that 1.5 to 1.6 is a more realistic estimate for the completeness magnitude for these parts of Oregon and Washington.

The coda magnitude of completeness in Oregon was higher than in Washington for the 1970's (Figures 5A and 5B), and has only approached that of Washington since the early 1990s. The station spacing shown in Figure 1, however, is consistent with the completeness threshold in western and southern Oregon remaining higher than in most parts of Washington. Due to the more sparse station density and less detailed station corrections there, fewer than 10% of earthquake locations in Oregon have quality locations of BB or higher. In contrast, nearly half (46%) of the earthquakes in the catalog for Washington state have BB or higher quality locations. Similar results are found for detonations. As a result of the geographic distribution of the stations, the highest quality locations for detonations are almost exclusively limited to western and central Washington.

About half of the detonations not listed in the ANSS and PNSN catalog were sited in Oregon from 1978 to 1984, when the lowest magnitude of completeness in Oregon was M=3 (Figure 5B), higher than the expected magnitude of these detonations (Table 2). We thus find reasonable correspondence between the two methods of estimating the low magnitude threshold of catalog completeness. The agreement is reasonable given that the detonations provide a detection magnitude, not a completeness magnitude. This comparison suggests that using detonations to help constrain completeness magnitudes is useful.

The average actual epicentral error for the 72 detonations that could be located in the Pacific Northwest was 1.9 km and their average depth error was 3.5 km; these errors are comparable to those determined for 163 surface detonations located by the Northern

California Seismic Network (NCSN) (Brocher, 2003a). However, the epicentral errors in Oregon are about twice as large and the depth errors are about 4 times larger than these regional averages (Table 3). In Northern California the average actual epicentral error was 2.1 km and the average hypocentral depth error was 2.8 km.

As noted previously, location errors for surface detonations may not be representative of location errors for earthquakes for several reasons. Brocher (2003a) determined that in the San Francisco Bay Area the actual location errors are about twice the formal estimates made from the network parameters used to locate blasts. Brocher (2003a) proposed that the larger actual errors result from travel paths for surface detonations that transect the shallow, low-velocity upper crust twice instead of once for typical deeper earthquake. This point may be even more important in areas like Puget Sound, where the depth of located events can exceed 60 km, resulting in even shorter (more vertical) travel paths in the shallow upper crust. Having stated this disclaimer, we feel that it is fair to compare the relative location errors for shallow detonations within the PNSN. This comparison shows that location and depth errors in Oregon are significantly higher than in Washington (Table 3), whereas regional differences within much of Washington are relatively subdued.

Summary

We used a compilation of 72 surficial detonations in Washington and Oregon to investigate a number of questions related to network-based event locations. Can published empirical magnitude-charge size relationships (equations 1 and 2), used for a variety of forensic and test ban treaty verification purposes, be extended to charge sizes as small as 57 kg? Our data indicate that they can. Are average location errors produced by the PNSN stations for these shallow detonations comparable to those produced by the NCSN for shallow detonations in northern California? Again, our data indicate that they are.

Are there regional variations in the completeness and quality of the earthquake catalog in Washington and Oregon? Once again, our compilation shows that there are important regional differences. The earthquake catalog in western Washington is both complete to lower magnitudes and has a 5 times higher percentage of high quality solutions than the catalog for western Oregon. Location and depth errors of shallow borehole detonations are 2 to 4 times higher in Oregon than in Washington. As a result, seismogenic crustal faults may be less well defined by microseismicity in western Oregon than they are in western Washington. Perhaps the most surprising finding of our study is that the actual location errors of detonations in the Puget Lowland can be unexpectedly large. Improving these locations is an important focus of future research.

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Figures

Figure 1. Map showing locations of the permanent seismic network stations (dots) in the Pacific Northwest from 1975 until mid-2001. Map extends from the southern boundary of Oregon to the northern boundary of Washington. For the years 1984 to 2000, the stations correspond to those available during the seismic refraction

experiment conducted in that year. Abbreviations: Cape Blanco, CB; Eugene, E; Hanford, H; Klamath Falls, KF; Portland, P; Seattle, S; Spokane, Sp; and Vancouver Island, VI.

Figure 2. Maps showing various aspects of the earthquake catalog for the refraction detonations that were located by the PNSN. (A) Magnitude reported for each detonation. Experiments (usually identifiable as lines of detonations) are labeled by the year of the study. Detonations not located by the PNSN are shown as filled circles (note differences in magnitude scale to make them visible). Expected maximum magnitudes for these detonations that were not located were calculated from equation 1. The 1965 quarry shot in Oregon was reported by Berg et al. (1966). Figures 2B to 2E show the sizes of the computed epicentral, latitude, longitude, and depth errors for the detonations that were located, respectively. Figures 2F to 2I show the RMS error, the number of stations used to locate the detonation, the distance to the closest station, and the largest azimuthal gap in stations, respectively. Abbreviations as in Figure 1.

Figure 3. Reported magnitude for the detonations in the ANSS and the PNSN catalogs versus the $\log_{10}$ charge size (in kg). Empirical relations between maximum magnitude and $\log_{10}$ (weight, kg) reported by Khalturin et al. (1999) for detonations in dry, hard rock (Equation 1) and by Gitterman and Shapira (2001) for water-fired detonations (Equation 2) are also plotted. Regression line (equation 3) for detonations in the Pacific Northwest is plotted as a dotted line.

Figure 4. Maps showing epicentral errors for the located refraction detonations and earthquakes for progressively higher-quality locations. (A) Epicentral errors for detonation locations containing only C and higher quality attributes. (B) Epicentral errors for detonation locations containing A or B as a first attribute and no lower than

C in the second attribute. (C) Epicentral errors for detonation locations containing only B or higher quality attributes. (D) Locations for all earthquakes between 1970 and 2000. (E) Earthquake locations between 1970 and 2000 containing only C and higher quality attributes. (F) Earthquake locations between 1970 and 2000 containing only A or B as a first quality attribute and no lower than C in the second quality attribute. All magnitudes plotted as a single symbol size. (G) Earthquake locations between 1970 and 2000 containing only B or higher quality attributes.

Figure 5. Plots of the logarithm of the cumulative frequency (per year) versus magnitude for (A) Washington, (B) Oregon, (C) northwestern Washington, (D) eastern Washington and Oregon, and (E) southwestern Washington and northwestern Oregon (geographic subregions are shown in lower right hand corner). Curves are shown for different years to illustrate the lowering of the magnitude threshold of catalog completeness. Dotted lines are fit to the portions of curves judged to be complete. Arrows show lowermost magnitude of completeness at different times. The Mount St. Helens earthquake sequence dominates the 1980-1985 curve for Washington and southwestern Washington. Both curves are deficient in earthquakes having magnitudes less than 3.8 due to (1) the desensitization of the network in order to minimize clipping the amplitudes of larger events and (2) the overprinting of the smaller events by the larger events. Thus, smaller events were located only during quiet intervals and larger events were located during active intervals. Aftershocks of Klamath Falls and Scotts Mills earthquakes caused the increased level of seismicity during the 1990-1995 interval for Oregon.

Figure 6. Summary of lower magnitude threshold of catalog completeness versus year based on the cumulative frequency versus magnitude curves in Figure 5. Catalog magnitudes of located detonations are superimposed, showing a decrease with time.

Expected maximum magnitudes of detonations not located by the networks in central Oregon in 1983 and 1984 lie just above the completeness limit (Oregon and Newberry in Table 2). A significant densification in the southern Oregon network following the Klamath Falls earthquakes in 1993 (Figure 1) likely lowered the local completeness magnitude at that time.

Table 1. Detonations listed in the Advanced National Seismic System (ANSS) and PNSN catalogs.

SP No.	Actual Longitude	Actual Latitude	Actual Elev. (m)	PNSN Longitude	PNSN Latitude	PNSN Depth (km)	PNSN Qual.	PNSN Magni-tude	Shot Yield kg	No. of Bore-holes	Hole Depth (m)	Wet or Dry?	Hand or Pump?	Eq. 1 Resid. Magn.	Shottime yy/mm/dd	Shottime hh:mm:ss	Shottime Differ. seconds	Name of Study
1	119.19578	46.970620	345	119.1953	46.9782	2.3	bb	2.7	1810	2	43	W	H	0.06	84/08/19	11:00:00	-0.07	Col. Plat.
3	119.83830	46.347947	472	119.8388	46.3450	0.1	bc	1.6	905	1	55		H	-0.82	84/08/19	11:04:00	0.04	Col. Plat.
2	119.46610	46.676223	126	119.4695	46.6768	0.0	bb	2.4	905	1	43	W	H	-0.02	84/08/19	11:32:00	0.05	Col. Plat.
1	119.19578	46.970620	345	119.1945	46.9780	2.2	bb	2.0	1810	2	49	W	H	-0.64	84/08/23	9:00:00	-0.04	Col. Plat.
2	119.46610	46.676223	126	119.4655	46.6760	0.0	ab	2.7	905	1	55	W	H	0.28	84/08/23	9:02:00	0.03	Col. Plat.
3	119.83830	46.347947	472	119.8270	46.3453	0.0	cc	2.1	905	1	43		H	-0.32	84/08/23	9:04:00	0.15	Col. Plat.
4	120.24629	45.940785	819	120.2465	45.9297	1.6	bc	2.3	1810	2	49		H	-0.34	84/08/23	9:06:00	0.16	Col. Plat.
9	121.95531	46.776340	1147	121.9450	46.7893	0.8	bc	1.1	1364	1	41	W	P	-1.45	91/09/24	6:00:00	0.10	PNW91
7	121.98857	47.337460	256	121.9762	47.3323	0.1	bc	2.1	909	1	42	W	P	-0.32	91/09/24	6:02:00	0.93	PNW91
5	122.06177	47.899020	42	122.0495	47.8990	0.0	bb	2.6	909	1	40		P	0.18	91/09/24	6:04:00	0.74	PNW91
3	122.21106	48.478340	279	122.1543	48.4743	0.0	bd	1.5	909	1	45		P	-0.92	91/09/24	6:06:00	0.47	PNW91
10	121.90090	46.491860	411	121.9103	46.4842	0.9	cc	1.7	1818	2	43	W	P	-0.94	91/09/24	9:00:00	0.00	PNW91
6	122.03147	47.690110	67	122.0107	47.6882	0.0	bc	1.2	909	1	58	W	P	-1.22	91/09/24	9:04:00	1.42	PNW91
4	122.10647	48.242110	114	122.0882	48.2492	0.0	cc	2.3	909	1	41	W	P	-0.12	91/09/24	9:06:00	0.35	PNW91
13	123.13479	46.281020	332	123.1392	46.2825	9.0	bc	1.5	909	1	43	W	P	-0.92	91/09/28	7:00:00	0.86	PNW91
11	123.11958	46.715300	122	123.1037	46.7133	5.8	ac	2.4	1818	2	53	W	P	-0.24	91/09/28	7:02:00	1.06	PNW91
15	123.18259	45.642760	276	123.1947	45.6585	7.7	bc	1.7	909	1	43		P	-0.72	91/09/28	7:04:00	1.37	PNW91
17	123.21644	44.996150	58	123.2032	45.0172	7.5	bd	1.5	909	1	43		P	-0.92	91/09/28	7:06:00	1.66	PNW91
19	123.31846	44.376060	81	123.3005	44.3783	4.9	cd	2.5	1364	1	42		P	-0.05	91/09/28	7:08:00	1.38	PNW91
14	123.14380	45.968190	305	123.1490	45.9707	19.6	bb	2.2	909	1	43		P	-0.22	91/09/28	9:00:00	1.21	PNW91
12	123.14212	46.494640	343	123.1457	46.5007	0.0	bb	1.6	1364	1	42		P	-0.95	91/09/28	9:02:00	0.45	PNW91
18	123.20181	44.688930	76	123.2130	44.6935	12.5	bd	2.3	909	1	55		P	-0.12	91/09/28	9:06:00	1.38	PNW91
20	123.39594	44.032890	290	123.3813	44.0298	3.4	cc	2.1	1818	2	43	D	P	-0.54	91/09/28	9:08:00	1.10	PNW91
21	124.00471	44.869780	189	123.8408	44.9692	9.3	bd	2.0	909	1	43		P	-0.45	91/10/02	9:00:03	0.42	PNW91
22	123.46821	44.839784	354	123.4900	44.8600	16.60	cd	0.0	909	1	46		P	-2.45	91/10/02	9:02:00	0.45	PNW91
23	122.67084	44.836920	363	122.7138	44.8488	0.0	bd	2.3	909	1	44		P	-0.15	91/10/02	9:06:00	0.90	PNW91
24	122.27847	44.847240	536	122.2998	44.8577	2.8	bc	1.8	909	1	47		P	-0.65	91/10/02	9:08:00	0.58	PNW91
15	123.18259	45.642760	276	123.1930	45.6575	7.7	bc	2.5	909	1	42		P	0.05	91/10/02	9:10:00	1.39	PNW91
11	123.11958	46.715300	122	123.1005	46.7130	6.1	ac	2.4	909	1	43		P	-0.05	91/10/02	9:12:00	1.05	PNW91
22	123.46821	44.839784	354	123.4792	44.8578	21.8	cd	1.9	454	1	46		P	-0.33	91/10/02	9:00:00	-0.23	PNW91
4E	123.24341	46.586800	233	123.2168	46.5902	0.0	bc	2.2	1810	2	45	W	P	-0.44	95/09/11	7:02:00	1.02	PNW95
17	119.85420	46.830600	248	119.8472	46.8453	0.0	ba	1.6	905	1	46	D	P	-0.82	95/09/11	7:04:00	-0.14	PNW95
9N	121.90259	46.496240	372	121.9060	46.4885	0.0	bc	1.4	1357	1	56	W	P	-1.15	95/09/11	7:06:00	-0.10	PNW95
15	120.34580	46.763900	703	120.3653	46.7453	4.4		1.4	905	1	46	D	P	-1.02	95/09/11	7:12:00	0.51	PNW95
6	122.76344	46.558550	162	122.7500	46.5600	6.1	ac	0.6	452	1	39	W	P	-1.60	95/09/11	7:14:00	1.51	PNW95
2	123.82080	46.578440	138	123.7958	46.5745	6.1	dc	1.8	2715	2	55	W	P	-0.97	95/09/11	10:00:00	1.19	PNW95
5E	123.00683	46.567050	194	123.0062	46.5653	7.4	bc	1.8	1357	1	55	W	P	-0.75	95/09/11	10:02:00	1.62	PNW95
7E	122.45888	46.568810	462	122.4607	46.5607	1.1	bc	1.7	905	1	43	W	P	-0.72	95/09/11	10:04:00	0.76	PNW95
8	122.18089	46.532280	633	122.1752	46.5172	3.1	bb	1.6	452	1	39	D	P	-0.60	95/09/11	10:06:00	0.81	PNW95
10	121.65920	46.585000	516	121.6700	46.5900	0.1	bb	0.7	452	1	40	D	P	-1.50	95/09/11	10:08:00	0.51	PNW95
12	121.15080	46.663600	1149	121.1493	46.6583	0.9	bc	1.1	452	1	40	D	P	-1.10	95/09/11	10:10:00	0.53	PNW95
15	120.34580	46.763900	703	120.3600	46.7400	4.4	bc	1.4	905	1	46	W	P	-1.02	95/09/11	10:12:00	0.31	PNW95

2	123.82080	46.578440	138	123.7975	46.5797	5.5	dc	1.3	1357	1	57	W	P	-1.25	95/09/15	7:00:00	1.30	PNW95
5W	123.00727	46.567250	192	122.9977	46.5662	7.0	bc	1.7	905	1	42	W	P	-0.72	95/09/15	7:02:00	1.70	PNW95
7W	122.46405	46.569040	435	122.4688	46.5600	2.4	bc	1.2	905	1	36	W	P	-1.22	95/09/15	7:04:00	0.94	PNW95
9S	121.90238	46.495850	374	121.9048	46.4907	0.0	bc	1.1	1357	1	55	W	P	-1.45	95/09/15	7:06:00	-0.07	PNW95
11	121.43110	46.630600	1499	121.4000	46.6400	0.0	bc	0.2	905	1	46	D	P	-2.22	95/09/15	7:08:00	0.38	PNW95
15	120.34580	46.763900	703	120.3740	46.7462	3.8		1.8	905	1	46	D	P	-0.62	95/09/15	7:12:00	0.39	PNW95
17	119.85420	46.830600	248	119.8492	46.8397	1.9		1.8	905	1	46	D	P	-0.62	95/09/15	7:14:00	0.06	PNW95
1	124.03874	46.597940	3	123.9638	46.5658	6.4	dd	2.1	905	1	32	W	P	-0.32	95/09/15	10:00:00	2.90	PNW95
4W	123.24449	46.586390	260	123.2227	46.5892	0.0	bc	1.4	452	1	41	W	P	-0.80	95/09/15	10:02:00	-3.05	PNW95
8	122.18089	46.532280	633	122.1758	46.5168	0.0	bb	1.3	452	1	38	D	P	-0.90	95/09/15	10:06:00	0.73	PNW95
10	121.65920	46.585000	516	121.6500	46.5800	0.0	bb	0.6	452	1	40	D	P	-1.60	95/09/15	10:08:00	0.60	PNW95
3	123.50309	46.580060	150	123.4707	46.5755	7.9	bc	1.2	905	1	47	W	P	-1.22	95/09/15	10:10:00	1.52	PNW95
16	120.11940	46.803300	604	120.1065	46.8098	2.9		1.1	2715	2	50	W	P	-1.67	95/09/15	10:12:00	0.38	PNW95
12	121.15080	46.663600	1149	121.1500	46.6500	0.5	bb	0.8	452	1	40	D	P	-1.40	95/09/15	10:14:00	0.60	PNW95
30	121.81239	47.663000	224	121.8393	47.6602	0.0	bc	1.2	113	1	25	W	P	-0.56	99/09/20	8:04:00	0.29	SHIPS99
1a	123.08653	47.708333	237	123.0443	47.7295	1.4	bb	1.5	1267	1	55	W	P	-1.03	99/09/20	9:30:00	0.64	SHIPS99
5a	122.94722	47.728667	414	123.0265	47.7307	15.4	ad	1.1	905	1	46	W	P	-1.32	99/09/20	9:31:59	-0.46	SHIPS99
32a	121.71790	47.653667	389	121.7095	47.6512	0.0	ba	1.6	905	1	43	W?	P	-0.82	99/09/20	9:36:00	0.20	SHIPS99
35	121.61656	47.664167	468	121.6115	47.6609	4.3	bb	2.7	1086	1	38	W	P	0.22	99/09/20	11:08:00	0.51	SHIPS99
11a	122.71821	47.708333	117	122.7647	47.6800	4.1	dc	1.4	226	1	27	D	P	-0.58	99/09/21	8:12:01	1.47	SHIPS99
5b	122.94582	47.718333	404	122.9288	47.7295	0.1	bc	1.6	905	1	46	W	P	-0.82	99/09/21	9:34:00	0.48	SHIPS99
32b	121.71790	47.651833	389	121.7163	47.6512	4.0	cb	1.7	905	1	43	W	P	-0.72	99/09/21	9:36:00	0.64	SHIPS99
11b	122.71831	47.679333	117	122.7320	47.6798	1.3	ac	1.6	226	1	27	D	P	-0.38	99/09/21	9:42:01	1.42	SHIPS99
21a	122.24941	47.674000	17	122.2532	47.6829	0.0	ba	1.3	181	1	27	W	P	-0.61	99/09/22	8:00:01	1.89	SHIPS99
18	122.41974	47.664667	73	122.4315	47.6645	0.0	bb	1.9	147	1	24	W	P	0.06	99/09/22	8:14:02	2.06	SHIPS99
21b	122.24881	47.681500	16	122.2462	47.6830	0.0	ba	1.7	181	1	21	W	P	-0.21	99/09/22	9:30:01	1.96	SHIPS99
22	122.17490	47.637667	155	122.1738	47.6514	0.0	bc	1.0	181	1	22	D	P	-0.91	99/09/22	9:34:01	1.87	SHIPS99
13	122.68767	47.683667	12	122.7212	47.6727	0.7	ad	1.3	57	1	24	W	P	-0.24	99/09/22	9:38:01	1.57	SHIPS99
17	122.54804	47.660667	85	122.5662	47.6541	2.9	ac	1.2	170	1	18	W	P	-0.69	99/09/22	9:40:02	2.18	SHIPS99
20	122.29871	47.635167	4	122.3033	47.6509	0.0	db	1.9	57	1	16	W	P	0.36	99/09/22	9:44:02	2.01	SHIPS99

Table 2. Detonations not listed by the Advanced National Seismic System (ANSS) and PNSN catalogs.

SP No.	Shot Longitude	Shot Latitude	Elev. (m)	Yield kg	No. Holes	Max. Mag.	Shottime mm/dd/yy	Shottime hh:mm:ss		Name of Study
	123.92148	44.820767	181	49774		3.7	09/23/65	0:00:00	*	Quarry shot
1	121.73867	45.519333	658	452	1	2.2	10/19/78	8:00:00	*	Mt. Hood
2	121.57312	45.359367	1030	452	1	2.2	10/19/78	8:15:00	*	Mt. Hood
3	121.72660	45.180750	1071	452	1	2.2	10/19/78	8:30:00	*	Mt. Hood
4	122.08243	45.304100	914	452	1	2.2	10/19/78	11:00:00	*	Mt. Hood
1	121.73867	45.519333	658	452	1	2.2	10/23/78	8:00:00	*	Mt. Hood
2	121.57312	45.359367	1030	452	1	2.2	10/23/78	8:15:00	*	Mt. Hood
3	121.72660	45.180750	1071	452	1	2.2	10/23/78	8:30:00	*	Mt. Hood
4	122.08243	45.304100	914	452	1	2.2	10/23/78	11:00:00	*	Mt. Hood
5	121.42533	45.432800	1059	452	1	2.2	10/23/78	11:15:00	*	Mt. Hood
6	122.06828	45.063283	512	452	1	2.2	10/23/78	11:30:00	*	Mt. Hood
3	121.72660	45.180750	1071	2700	2	2.8	11/01/78	9:00:00	*	Mt. Hood
7	122.11783	44.365950	1134	1360	1	2.6	11/01/78	9:15:00	*	Mt. Hood
8	122.50955	42.848133	945	2700	2	2.8	11/01/78	9:30:00	*	Mt. Hood
6	119.52100	43.616055	1311	452	1	2.2	10/11/83	6:00:00	*	Oregon
5	120.87951	43.695610	1540	452	1	2.2	10/11/83	6:15:00	*	Oregon
1	121.64687	43.700127	1312	452	1	2.2	10/11/83	6:30:00	*	Oregon
3	121.22835	43.710605	2011	452	1	2.2	10/14/83	5:30:00	*	Oregon
7	118.85600	43.654205	1353	452	1	2.2	10/14/83	5:45:00	*	Oregon
4	121.04068	43.697598	1618	452	1	2.2	10/14/83	6:00:00	*	Oregon
2	121.42661	43.701660	1318	452	1	2.2	10/14/83	7:00:00	*	Oregon
5	120.87951	43.695610	1540	452	1	2.2	10/14/83	7:30:00	*	Oregon
6	119.52100	43.616055	1311	452	1	2.2	10/14/83	7:45:00	*	Oregon
1	121.64687	43.700127	1312	452	1	2.2	10/14/83	8:30:00	*	Oregon
9	121.54517	43.983500	1672	2720	2	2.8	08/28/84	5:00:00	*	Newberry
16	121.59450	42.982833	1378	2720	2	2.8	08/28/84	5:02:00	*	Newberry
11	120.74283	43.674667	1466	2720	2	2.8	08/28/84	5:04:00	*	Newberry
14	120.67217	44.401167	1082	2720	2	2.8	08/28/84	5:06:00	*	Newberry
8	121.73433	43.715167	1322	2720	2	2.8	08/28/84	8:00:00	*	Newberry
12	121.07267	43.400167	1327	2720	2	2.8	08/28/84	8:02:00	*	Newberry
15	120.40200	43.251500	1311	2720	2	2.8	08/28/84	8:04:00	*	Newberry
10	121.08183	43.064000	1038	2720	2	2.8	08/28/84	8:06:00	*	Newberry
13	121.53833	43.453333	1335	2720	2	2.8	08/28/84	10:00:00	*	Newberry
1	122.17978	48.946400	606	1818	2	2.7	09/24/91	6:08:00	*	PNW91
2	122.16451	48.727610	219	1364	1	2.6	09/24/91	9:08:00		PNW91
8	122.02650	47.088680	430	909	1	2.5	09/24/91	9:02:00		PNW91
16	123.24969	45.329900	179	909	1	2.5	09/28/91	9:04:00		PNW91
17	123.21643	44.996150	58	909	1	2.5	10/02/91	9:04:00		PNW91
11	121.43110	46.630600	1499	905	1	2.4	09/11/95	7:08:00	*	PNW95
13	120.92920	46.690300	852	23	1	1.3	09/11/95	7:10:00	*	PNW95
14	120.66390	46.739700	593	679	1	2.4	09/11/95	7:00:00	*	PNW95
14	120.66390	46.739700	593	905	1	2.4	09/15/95	7:10:00	*	PNW95
6	122.76344	46.558550	162	452	1	2.2	09/15/95	10:04:00	*	PNW95
2	123.05640	47.741223	155	113	1	1.8	09/20/99	8:00:00	*	SHIPS99
6	122.89234	47.707970	5	23	1	1.3	09/20/99	8:02:00	*	SHIPS99
31	121.75862	47.655139	355	113	1	1.8	09/20/99	8:06:00	*	SHIPS99
34	121.64273	47.653562	467	113	1	1.8	09/20/99	8:08:00	*	SHIPS99
29	121.86075	47.657893	129	113	1	1.8	09/20/99	9:34:00		SHIPS99
4	122.99155	47.716137	136	113	1	1.8	09/21/99	8:00:00	*	SHIPS99
9	122.77913	47.693580	86	23	1	1.3	09/21/99	8:02:00	*	SHIPS99
33	121.67274	47.652125	526	113	1	1.8	09/21/99	8:06:00	*	SHIPS99
10	122.72474	47.699421	121	68	1	1.6	09/21/99	8:10:00		SHIPS99
1	123.08653	47.729520	238	113	1	1.8	09/21/99	9:30:00	*	SHIPS99
8	122.80158	47.705836	44	113	1	1.8	09/21/99	9:32:00	*	SHIPS99
27	121.93055	47.672020	9	113	1	1.8	09/22/99	8:04:00	*	SHIPS99
26	121.94642	47.644160	158	113	1	1.8	09/22/99	8:06:00	*	SHIPS99
14	122.63156	47.677027	73	23	1	1.3	09/22/99	8:08:00	*	SHIPS99
15	122.57815	47.661350	45	23	1	1.3	09/22/99	8:10:00	*	SHIPS99
19	122.34588	47.668744	79	11	1	1.1	09/22/99	8:12:00		SHIPS99
26	121.94642	47.644160	158	113	1	1.8	09/22/99	9:36:00	*	SHIPS99
19	122.34588	47.668744	79	11	1	1.1	09/22/99	11:12:00	*	SHIPS99
1	122.39870	47.530441	56	68	1	1.6	03/26/00	11:44:00		SHIPS00
2	122.25225	47.562026	8	68	1	1.6	03/26/00	11:46:00	*	SHIPS00
3	122.24875	47.682952	16	68	1	1.6	03/26/00	11:48:00	*	SHIPS00
4	122.41973	47.664689	73	68	1	1.6	03/26/00	11:50:00		SHIPS00

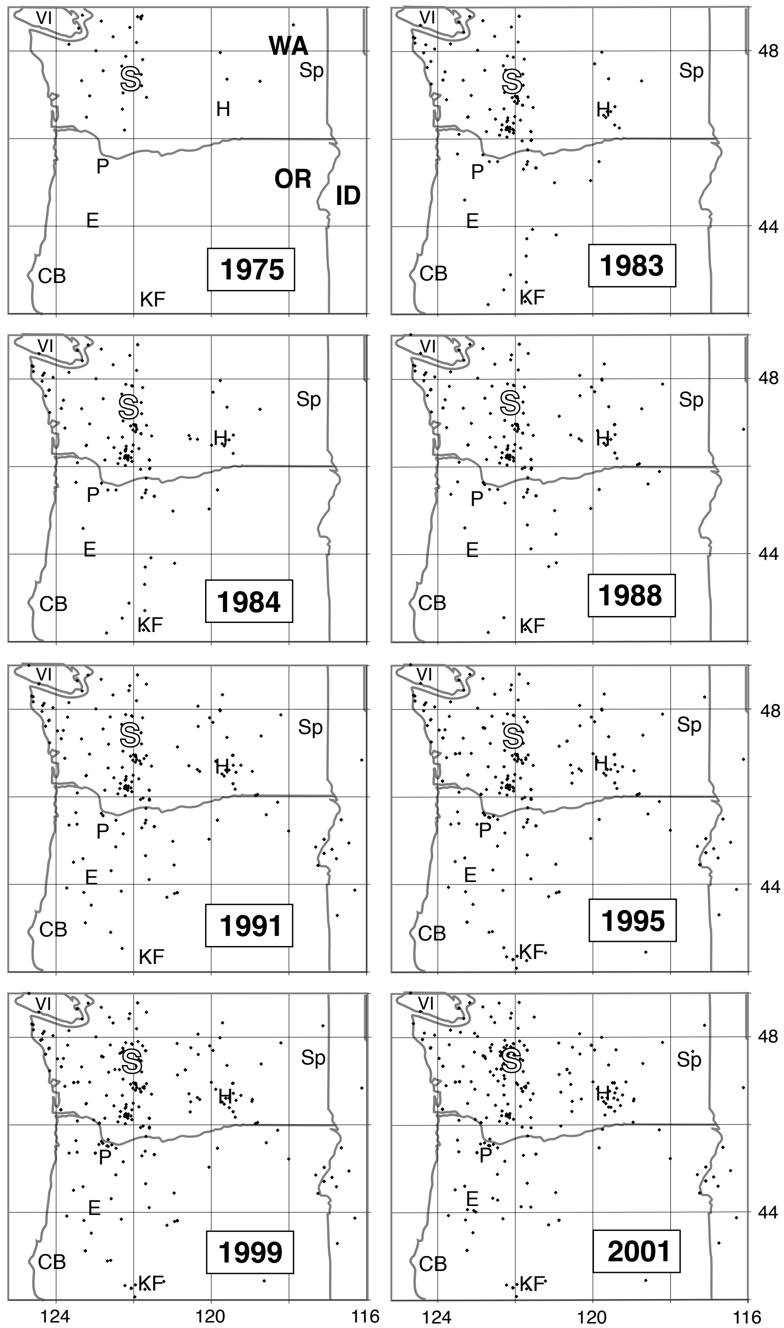
*Detonation was detected by the PNSN or its predecessors but was not locatable.

Table 3. Summary of average location and depth errors and PNSN location parameters for detonations

Location	Latitude Error (km)	Longitude Error (km)	Epicentral Error (km)	Depth Error (km)	Ave. Magnitude	No. of Stations Used	Largest Azimuthal Gap (°)	Nearest Station (km)	RMS Err. (s)	No. of Shots
All shots	1.05	1.33	1.86	3.46	1.65	24	97	18	0.24	72
Oregon	2.01	2.10	3.04	8.88	1.93	16	143	41	0.20	13
Washington	0.84	1.16	1.60	2.26	1.58	26	86	13	0.25	59
E. Wash.	1.04	0.66	1.30	1.83	1.88	25	78	12	0.24	11
W. Wash.	0.78	1.29	1.68	2.37	1.51	26	89	13	0.25	47
Puget Low.	0.78	1.55	1.90	1.63	1.64	22	85	10	0.24	21

Table 4. Details of the loading and detonation procedures for the seven least and most efficient shotholes

SP No.	**PNSN Magnitude**	**Excess Magnitude**	**Geology**	**Shot Yield, kg**	**Wet or Dry?**	**Hand or Pump?**	**No. of Boreholes**	**Fly Rock?**	**Cratering?**	**Geyser?**	**Casing Blown?**	**Depth to tamp (m)**	**Hole Depth (m)**	**UTC Shottime yy/mm/dd**	**UTC Shottime hh:mm:ss**	**Name of Study**
Least	Efficient	Detonations														
11	0.2	-2.22		905	Dry	Pump	1		No	Yes	No		46	95/09/15	7:08:00	PNW95
16	1.1	-1.67		2715	Dry	Pump	2		No	Yes	No	9	50	95/09/15	10:12:00	PNW95
6	0.6	-1.60	Clay, sand, gravel	452	Wet	Pump	1		No	No	No	10	39	95/09/11	7:14:00	PNW95
10	0.6	-1.60		452	Dry	Pump	1		Yes	Yes	Yes	12	40	95/09/15	10:08:00	PNW95
10	0.7	-1.50		452	Dry	Pump	1		Yes	Yes	Yes	9	40	95/09/11	10:08:00	PNW95
9	1.1	-1.32	Shale	909	Wet	Pump	1						58	91/09/24	6:00:00	PNW91
9S	1.1	-1.45		1357	Wet	Pump	1		Yes	Yes	Yes	22	55	95/09/15	7:06:00	PNW95
			Average	1035								12.3	46.6			
Most Efficient Detonations																
18	1.9	0.06	Glacial deposits	147	Wet	Pump	1	No	-	No	No	5	24	99/09/22	8:14:02	SHIPS99
1	2.7	0.06	Basalt	1810	Wet	Hand	2						43	84/08/19	11:00:00	Col. Plat.
15	2.5	0.08	Clay	909	Dry	Pump	1	Minor	No	Yes	No	1	42	91/10/02	9:10:00	PNW91
5	2.6	0.18	Clay	909	Wet	Pump	1	No	No	No	No	0	40	91/09/24	6:04:00	PNW91
35	2.7	0.22	Glacial deposits	1086	Wet	Pump	1	Some	No	No	No	3	38	99/09/20	11:08:00	SHIPS99
2	2.7	0.28	Sandstone	905	Wet	Hand	1						55	84/08/23	9:02:00	Col. Plat.
20	1.9	0.36	Glacial deposits	57	Wet	Pump	1	No	No	No	No	6	16	99/09/22	9:44:02	SHIPS99
			Average	832								3.0	36.9			



VI
WA
Sp
S
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OR
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E
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1975
1983
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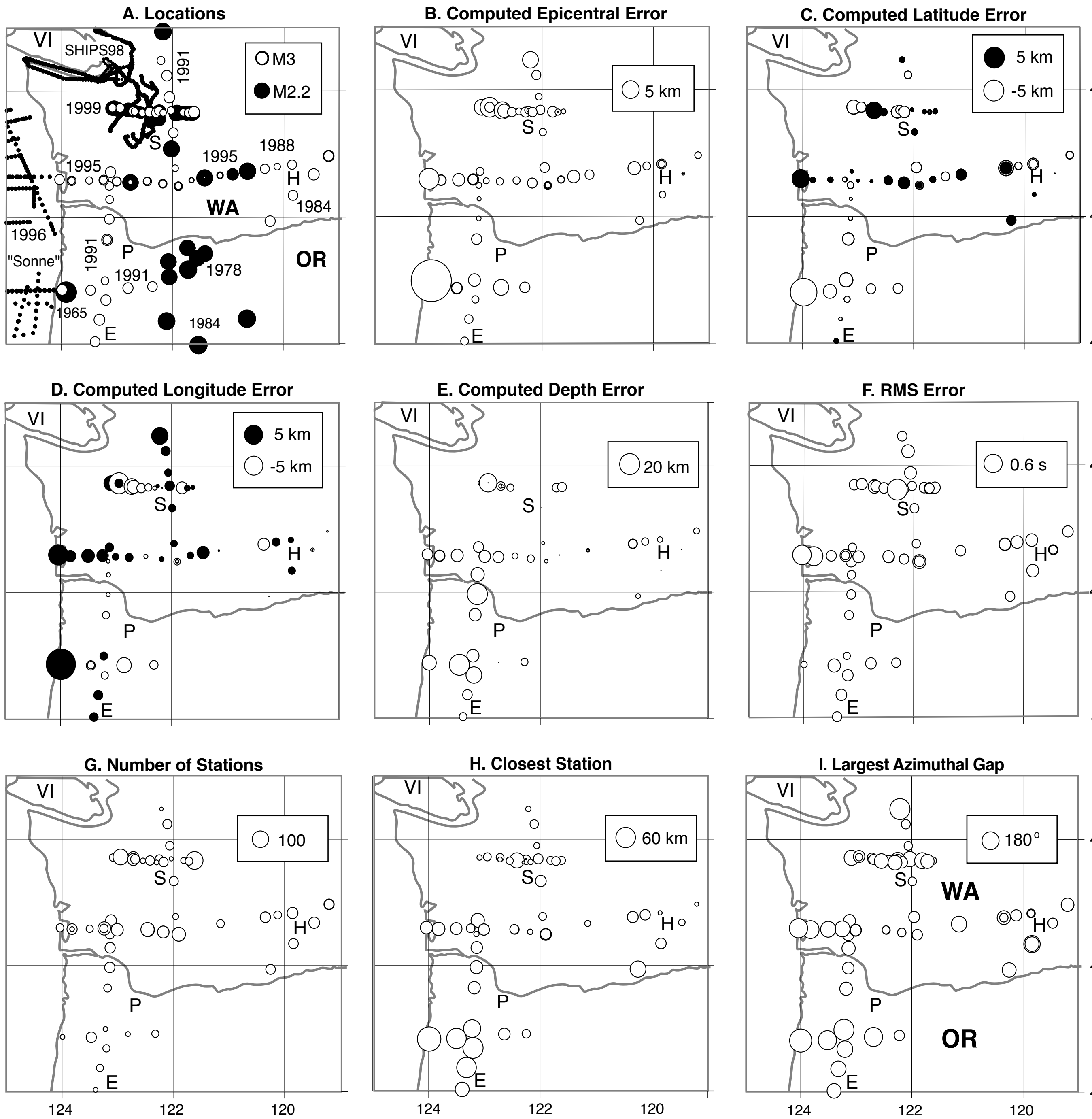
44
124
120
116



A. Locations
B. Computed Epicentral Error
C. Computed Latitude Error
D. Computed Longitude Error
E. Computed Depth Error
F. RMS Error
G. Number of Stations
H. Closest Station
I. Largest Azimuthal Gap
M3
M2.2
SHIPS98
1999
1991
1995
1988
1984
1996
"Sonne"
1965
1978
VI
S
P
E
H
WA
OR
5 km
-5 km
20 km
0.6 s
100
60 km
180°
48
46
44
124
122
120

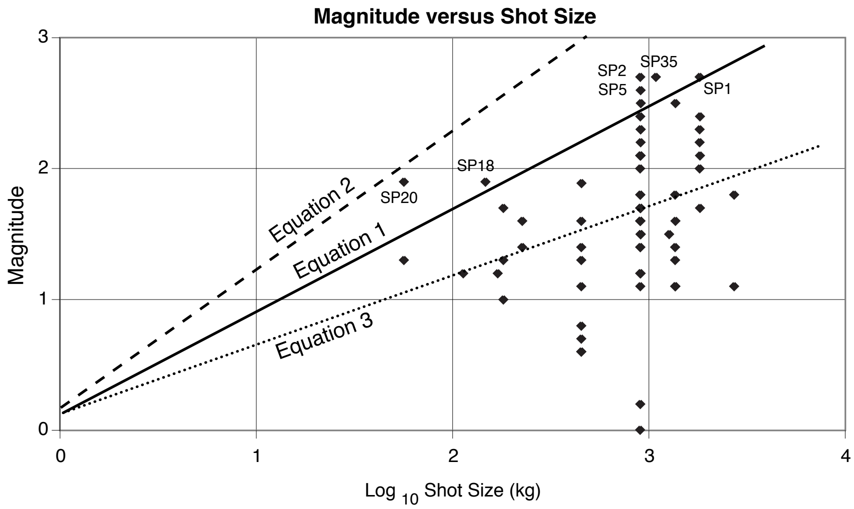


Figure 3. Brocher, Weaver, and Ludwin

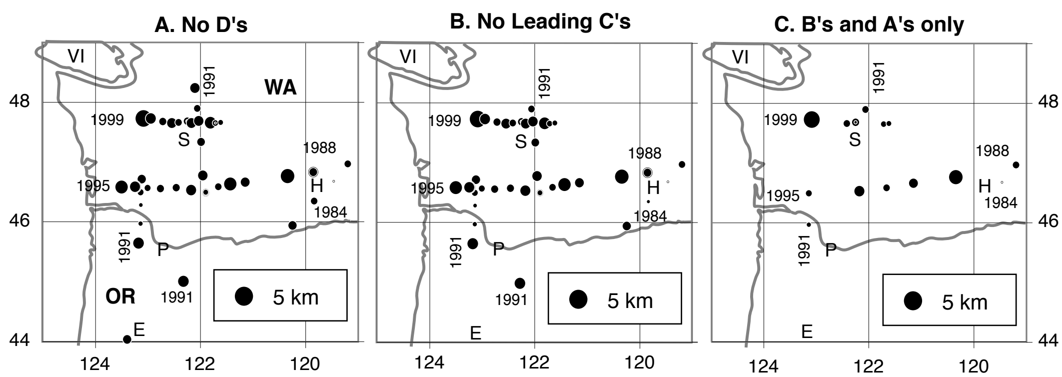


Figure 4. Brocher, Weaver, and Ludwin

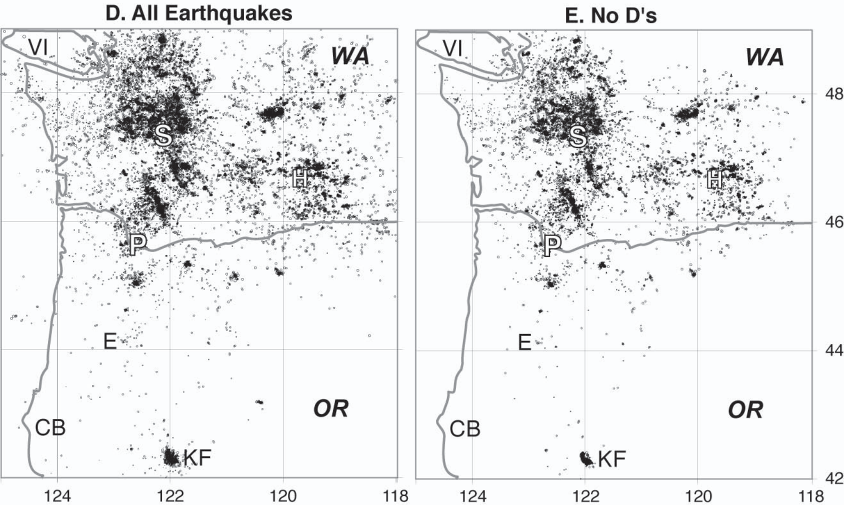


Figure 4 continued. Brocher, Weaver, and Ludwin

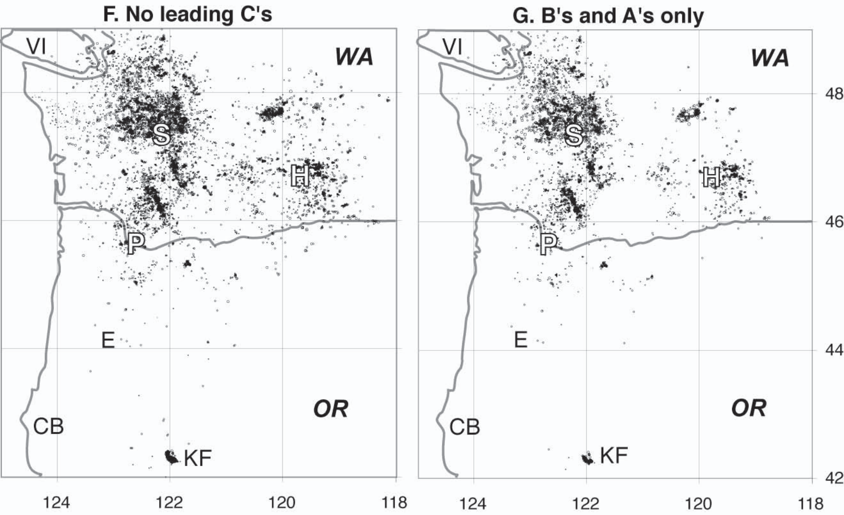


Figure 4 continued. Brocher, Weaver, and Ludwin

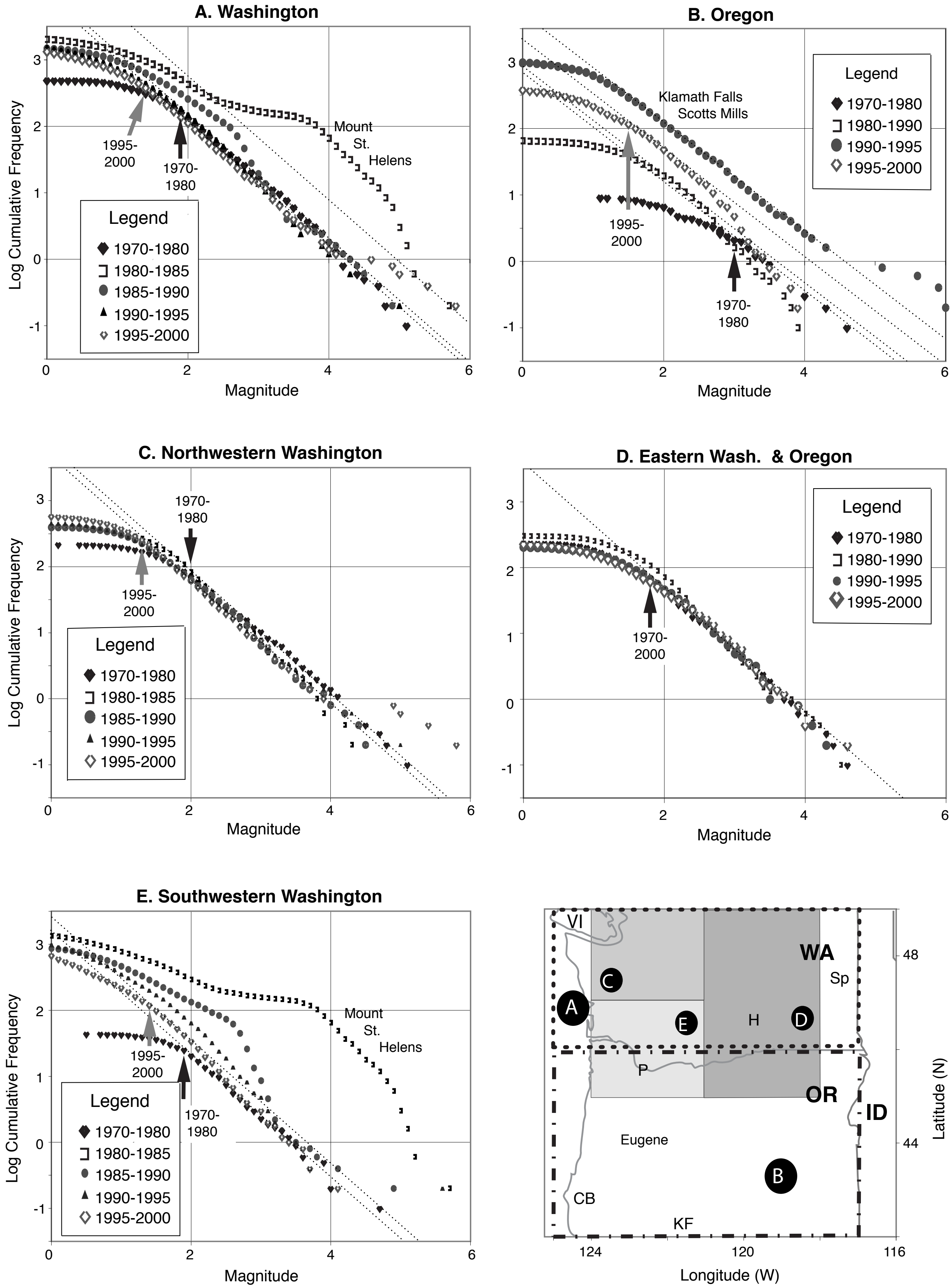


Figure 5. Brocher, Weaver, and Ludwin

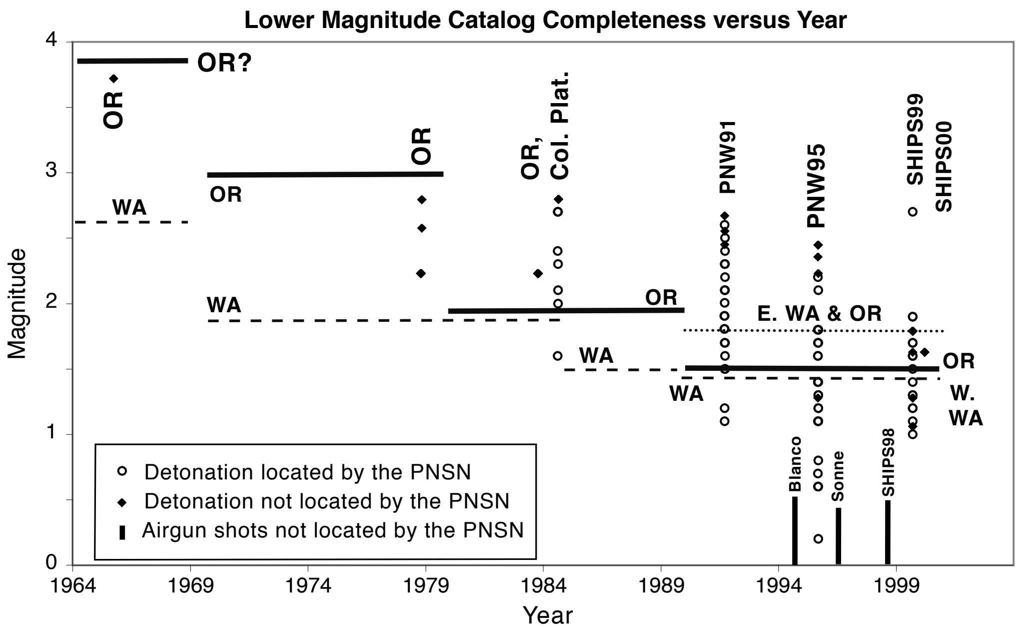


Figure 6. Brocher, Weaver, and Ludwin